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RESEARCH MEMORANDUM

EFFECTIVENESS OF THERMAL-PNEUMATIC AIRFOIL-ICE-PROTECTION SYSTEM

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SUMMARY

Icing and drag investigations were conducted in the NACA Lewis icing research tunnel employing a combination thermal-pneumatic de-icer mounted on a 42-inch-chord NACA 0018 airfoil. The de-icer consisted of a 3-inch-wide electrically heated strip symmetrically located about the leading edge with inflatable tubes on the upper and lower airfoil surfaces aft of the heated area. The entire de-icer extended to approximately 25 percent of chord.

A maximum power density of 9.25 watts per square inch was required for marginal ice protection on the airfoil leading edge at an air temperature of 0° F and an airspeed of 300 miles per hour.

Drag measurements indicated that without icing, the de-icer installation increased the section drag to approximately 140 percent of that of the bare airfoil; with the tubes inflated, this value increased to a maximum of approximately 620 percent. A 2-minute tube-inflation cycle prevented excessive ice formation on the inflatable area although small scattered residual ice formations remained after inflation and were removed intermittently during later cycles.

Effects of the time lag of heater temperatures after initial application of power and the insulating effect of ice formations on heater temperatures were also determined.

INTRODUCTION

In the past, most of the commercial ice-protection equipment used on airplane wings has been of the pneumatic type or, in some cases, electrically heated boots; more recently, a hot-gas system has been used. The pneumatic type provides icing protection without necessitating a large supply of electric power, as is required for an electric system but a larger drag loss results and some ice formation must be tolerated to permit cyclic ice removal using the inflatable tubes. The cap of ice that forms at the leading edge of the airfoil during icing conditions is very difficult to remove and during most cyclic electric de-icing operations is removed only with special provision. A thermal and pneumatic de-icing system was therefore devised to provide electric icing protection at the leading edge with cyclic pneumatic protection rearward on both airfoil surfaces.

The investigation of the thermal-pneumatic system was conducted in 1945 in the NACA Lewis icing research tunnel at the request of the Air Materiel Command and the information is being made more generally available because of the inquiries that have been received regarding this type system. The study was made to determine the aerodynamic performance of the bare airfoil as compared with the airfoil with de-icer installed, using inflated and deflated conditions of the pneumatic tubes. The effectiveness of the unit as a satisfactory de-icer was also determined together with the electric-heating requirements at the leading edge of the airfoil. The results presented apply to a specific installation and are not necessarily representative of all systems of this general type.

APPARATUS

The experimental thermal-pneumatic de-icer was installed in the icing research tunnel on an NACA 0018 airfoil having a chord of 42 inches and a span of 36 inches. The airfoil was mounted from the ceiling of the throat section (fig. 1) approximately 11 feet downstream of a spray strut that atomized water to produce an icing cloud.

The inflation and deflation of the pneumatic de-icer tubes was controlled by a snap-action solenoid distributor valve; a vacuum pump was connected to the exhaust side to prevent auto inflation due to a pressure differential between the inside and the outside of the de-icer tubes.

Construction of de-icer. - Details of the installation and construction of the de-icer are shown in figure 2. The de-icer was approximately 0.1 inch thick and consisted of an electrically heated strip 3 inches wide and $33\frac{1}{3}$ inches long cemented symmetrically about the leading-edge chord line, with 32 inflatable tubes extending spanwise and spaced on approximately 13/16-inch centers, 16 on either side of the airfoil adjacent to the electrically heated area. The inflatable tubes were made of neoprene-covered stretchable nylon fabric, requiring an air pressure of from 25 to 30 pounds per square inch for inflation. The tubes were 3/4 inch wide and extended rearward to approximately 25-percent chord. The air supply was valved to allow alternate inflation of adjacent tubes (primary and secondary) on both sides of the airfoil.

The heater element consisted of number 34 chromel wires located approximately 0.020 inch from the external surface, with several thicknesses of glass fabric and neoprene on either side of the wire, as shown in figure 2. The wire elements were spaced chordwise at 1/8-inch intervals.

Instrumentation. - Two groups of three thermocouples each were mounted at the midspan position on the airfoil between plies of the heater to indicate the heat flow inward and outward. One group of thermocouples was located at the leading edge and the other approximately $1\frac{1}{4}$ inch from the leading-edge center line. Each group consisted of a thermocouple on the outside surface, one adjacent to a heater wire, and one on the airfoil skin under the heater.

Temperatures were measured on an automatic flight recorder and a recording wattmeter was used to measure the power to the heating element. A wake rake, installed in the tunnel about 10.5 inches (25-percent chord) downstream of the airfoil, was employed to measure the aerodynamic drag of the airfoil as affected by the de-icer installation and by ice accretion on the model.

CONDITIONS AND PROCEDURE

Aerodynamic investigation. - The aerodynamic portion of the investigation to obtain drag measurements was conducted on the airfoil model with and without the de-icer installed. The experiments were conducted at airspeeds of 150 and 250 miles per hour and at an angle of attack of 0°. With the de-icer installed on the airfoil, data were taken for the following conditions: (1) tubes deflated with no ice, (2) tubes deflated with ice, (3) primary tubes inflated with no ice, and (4) secondary tubes inflated with no ice. Drag values were obtained from pressure measurements taken in the wake of the airfoil by applying the momentum method used in reference 1. Although the drag values measured were not evaluated for cross-flow effects, these effects probably would not materially alter the over-all conclusions regarding the drag characteristics of this ice-protection system.

Determination of minimum power densities required for marginal icing. - The icing investigation was conducted using a simulated icing cloud, which contained an effective droplet size of approximately 35 microns based on volume maximum and a liquid-water content of approximately 2 grams per cubic meter measured at an airspeed of 200 miles per hour. This condition caused icing over the entire area of the de-icer and is considered an extreme maximum icing condition, which probably would be experienced in the atmosphere only intermittently; therefore, this condition is considered a severe test for the de-icer. Angles of attack of 0° and 4° were employed and airspeeds were varied from 150 to 300 miles per hour with air temperatures of 0°, 10°, and 20° F.

A minimum power density to the leading-edge heater was obtained for each condition by sufficiently reducing an initial excess power during a stabilized icing condition to allow only a trace of ice to form over the heater. This condition thus prevented formation of an ice cap over the leading edge, which is difficult to remove and is conducive to heater failure because of overheating under the ice. With minimum power density therefore, a maximum water flow occurred from the heater rearward onto the inflatable section where it was frozen and removed by pulsations of the tubes.

Cycle-time experiments resulted in the selection of a 2-minute inflation cycle. Primary and secondary tubes (fig. 1) were alternately inflated in succession to full inflation, which required approximately 7 seconds per set of tubes; all tubes were deflated during the remaining 106 seconds of the cycle.

A series of time-temperature studies of the heater were obtained during a nonicing condition at an airspeed of 250 miles per hour, an air temperature of 14° F, and a power density to the heater of 5.2 watts per square inch. Temperatures at each of the six thermocouple locations in the heater were recorded at approximately 26-second intervals throughout the heat-on period of the power cycle.

RESULTS AND DISCUSSION

The investigation of the de-icer included only sufficient data to establish the effectiveness of the de-icer operation and some evidence of the penalties to be expected with the use of such a system. Measurements for extensive correlation and analytical study were not obtained.

Drag values calculated from total-pressure measurements show that at 280 miles per hour and an angle of attack of 0°, installation of the de-icer without tube inflation resulted in a drag increase 140 percent greater than that of the bare airfoil during nonicing conditions. When the secondary tubes were inflated, the drag increased to 470 percent of that of the bare airfoil and, with the primary tubes inflated, this value was increased to 620 percent. Previous investigation (reference 2) of the increase in drag caused by three inflated tubes located near the leading edge of an NACA 23012 airfoil section showed a maximum drag increase of 136 percent of the bare airfoil drag at 270 miles per hour. The entire de-icer covered approximately 6.5-percent chord as compared with 25-percent-chord coverage for the model discussed herein. In considering the drag increases caused by tube inflation, however, normal operation would cause such penalties intermittently for only short periods of time.

Observations of the de-icer during both operation of the electrically heated leading-edge section and cyclic operation of the inflatable tubes showed that with marginal electric power applied to the thermal section operation of the inflatable tubes did not completely remove the ice formations on the pneumatic section of the de-icer. Very small ice formations adhered to the fillet strips between tubes at scattered points along the span but were always removed before reaching excessive size. Any localized ice formation that was not removed by one or two inflation cycles was usually completely removed by a third inflation cycle. Drag measurements indicated that with complete icing protection on the thermal section, scattered residual ice formations on the pneumatic section after an inflation cycle produced losses approximately equal to the losses caused by ice that formed during the remainder of the cycle. Operation of the tubes, however, did satisfactorily prevent cumulative formations of ice and excessive drag.

The effect of icing on drag with variations in power density of the heater but without operation of the pneumatic system is shown in figure 4 for airspeeds of 150 and 250 miles per hour and air temperatures of 0° and 20° F.

At 0° F and 250 miles per hour, 7.5 watts per square inch was insufficient for marginal ice protection on the leading-edge area so that after 5 minutes of icing, the power density was increased to 8 watts per square inch, which caused shedding of ice but only after considerable ice build-up. At an air temperature of 20° F, 3.0 watts per square inch was sufficient to cause shedding of ice with a resultant decrease in drag after 5 minutes of icing.

With a reduction of airspeed from 250 to 150 miles per hour at an air temperature of 20° F, 3.0 watts per square inch was excessive and after 10 minutes of icing, the power density was reduced to 2.0 watts per square inch. After 16 minutes the power density was further reduced to 1.75 watts per square inch without reaching a marginal icing condition. With an additional reduction in power density to 1.5 watts per square inch, however, excessive icing occurred.

A considerable lag was found to exist in the effective shedding of ice from the heated leading-edge area after the power was applied for all conditions of power density. A time history of temperatures through the heater at the leading-edge midspan position during an application of power is shown in figure 5. These results were obtained during a nonicing period at an airspeed of 250 miles per hour, an air temperature of 14° F, and a power density of 5.2 watts per square inch. The surface and wire temperatures stabilized in approximately 100 seconds and the airfoil-skin temperature required approximately 240 seconds. These results indicate that the outer surface of the de-icer responds rather quickly to the application of heat but that the airfoil skin because of its large metal mass requires additional time to reach thermal equilibrium. The drag measurements shown in figure 4 indicate that even though the surface temperature stabilizes in 100 seconds so that the inner face of the ice is melted, several additional minutes are required to produce actual shedding of the ice. Observation of an iced surface over a heater reveals erratic movement of water under the ice long before the ice cap becomes sufficiently unbalanced to shed or for the heat to melt through the ice to initiate shedding.

The power densities required for marginal icing protection with variation in airspeed at air temperatures of 0°, 10°, and 20° F are shown in figure 6. These data were taken at an angle of attack of 4° except one condition at 10° F, which was taken at 0° angle of attack. A maximum power density of 9.25 watts per square inch was found necessary for marginal ice protection at an air temperature of 0° F and an airspeed of 300 miles per hour. As airspeeds decreased and air temperatures increased, power densities decreased. Measurements of marginal power densities at 10° F indicate that a change in angle of attack from 0° to 4° has negligible effect on the power requirements.

Measurements of temperature on the external surface and within the heater, as shown in figure 7, were obtained during icing conditions and at an air temperature of 10° F. The first evidence of ice was observed to occur directly over the leading-edge thermocouples. In every case except at the lowest power density (fig. 7(d)), the de-icer outer surface and wire temperatures were higher than those temperatures measured on the airfoil skin. The airfoil-skin temperatures for each group of thermocouples were approximately equal even though a large gradient existed between the wire temperature at the two locations. This "leveling out" of the skin temperatures is attributed to the high conductivity of the metal.

SUMMARY OF RESULTS

The following results were obtained from an icing investigation conducted in the NACA Lewis icing research tunnel using a thermal-pneumatic de-icer mounted on a 42-inch-chord NACA 0018 airfoil.

1. Excessive ice formation was prevented on the inflatable areas when the pneumatic tubes were operated on a 2-minute inflation cycle with continuous electric heating at the leading edge.

2. During nonicing conditions the installation of the de-icer with no tubes inflated resulted in a drag increase approximately 140 percent greater than that of the bare airfoil. This value increased to a maximum of approximately 620 percent with tube inflation.

3. With complete icing protection on the leading-edge thermal section of the de-icer and with the tubes operating on a 2-minute inflation cycle, drag measurements indicated that scattered residual ice formations on the pneumatic section after an inflation cycle produced drag losses approximately equal to the drag incurred by ice that formed during the remainder of the cycle.

4. A maximum power density of 9.25 watts per square inch was required for marginal ice protection of the airfoil leading edge at an air temperature of 0° F and an airspeed of 300 miles per hour.

5. After an initial application of power to the thermal section, approximately 100 seconds were required for stabilization of the surface temperatures with several additional minutes required for effective shedding of leading-edge ice formations.

6. With marginal power densities, small ice formations over the heated area effectively insulated the surface so that the surface temperatures were in some cases increased far above freezing before shedding of ice occurred.

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1. Goett, Harry J.: Experimental Investigation of the Momentum Method for Determining Profile Drag. NACA Rep. 660, 1939.

2. Robinson, Russell G.: The Drag of Inflatable Rubber De-icers. NACA TN 669, 1938.

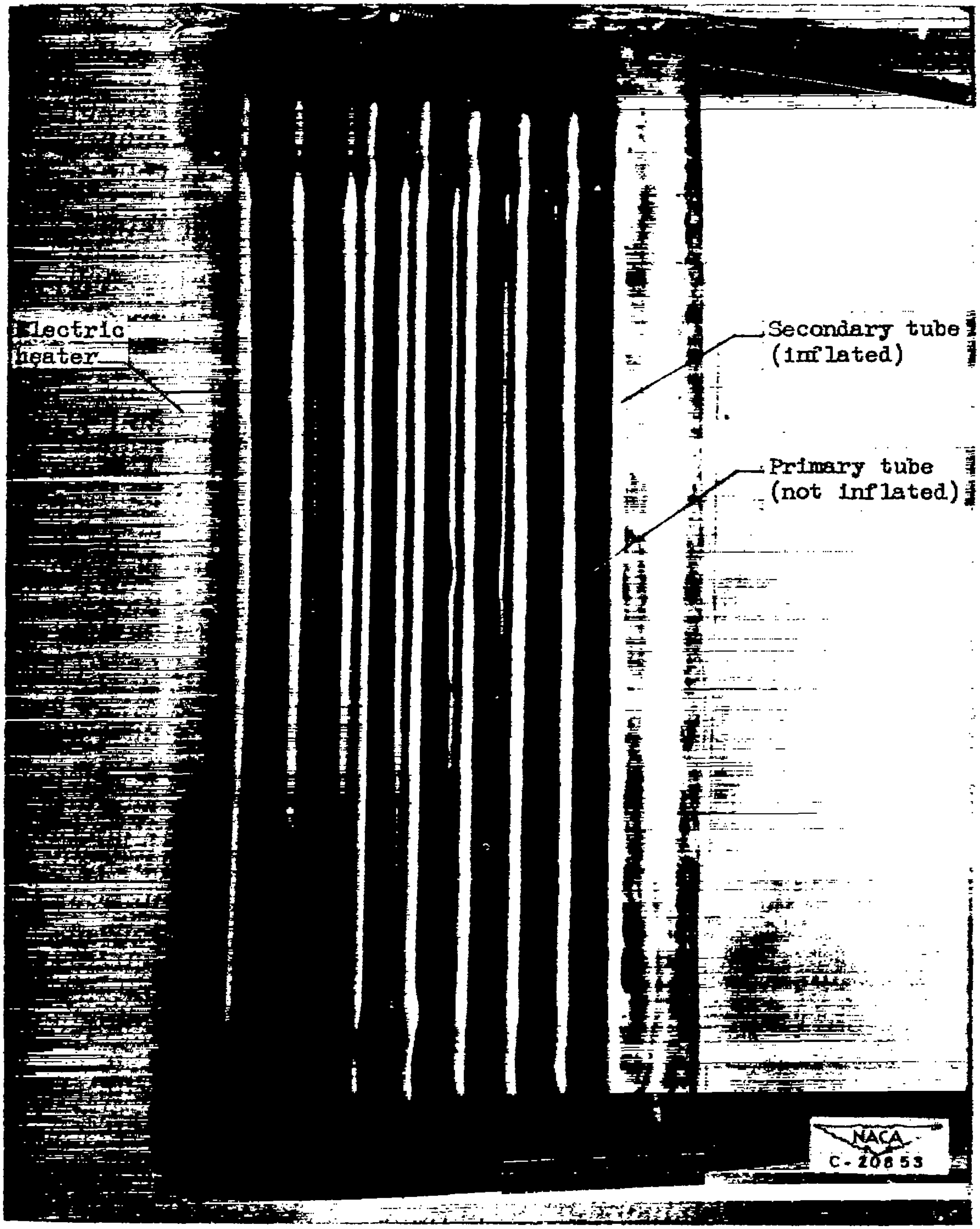


Figure 1. - Tunnel installation of thermal-pneumatic de-icer mounted on NACA 0018 airfoil showing secondary tubes inflated.

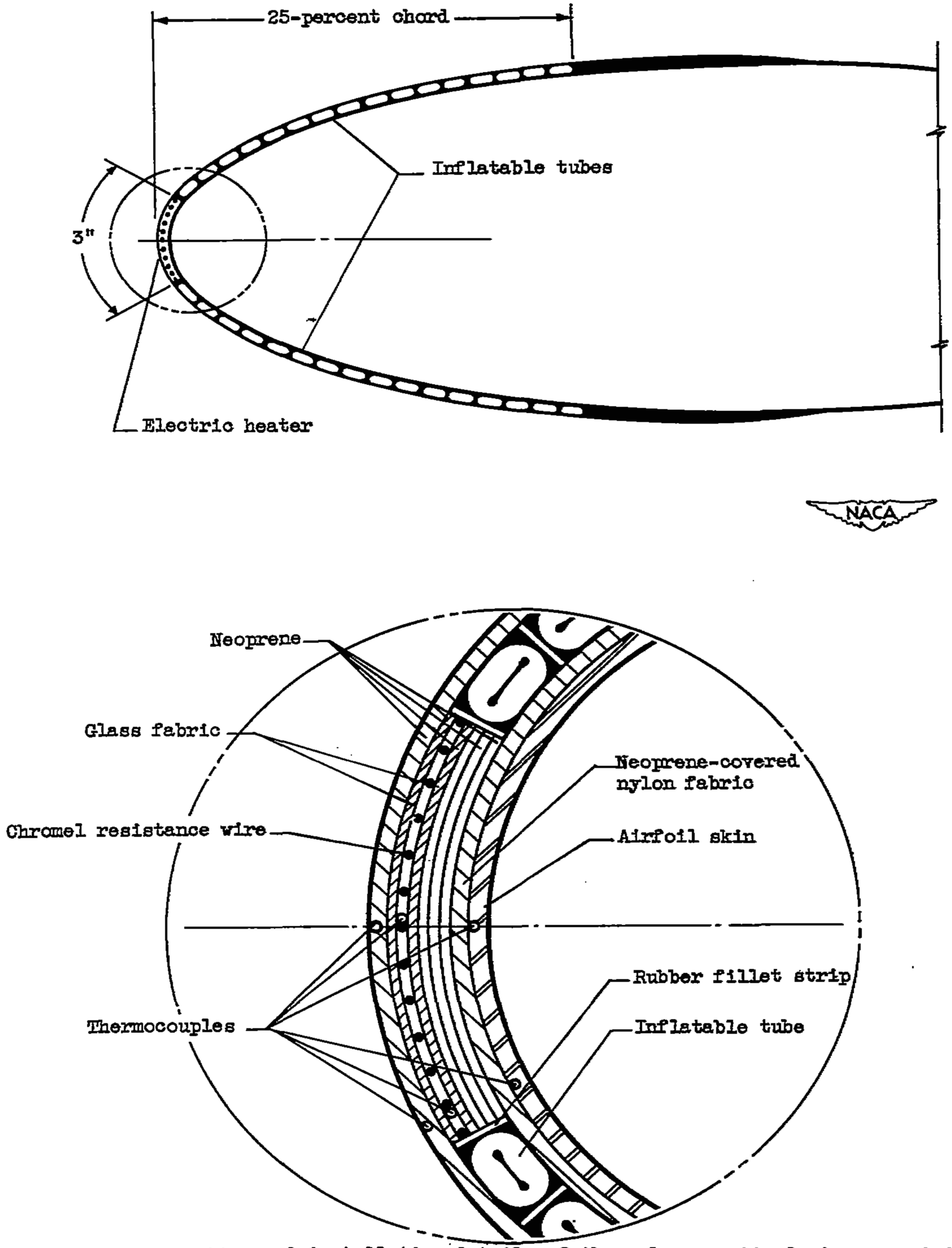


Figure 2. - Construction and installation details of thermal-pneumatic de-icer mounted on 42-inch-chord NACA 0018 airfoil.

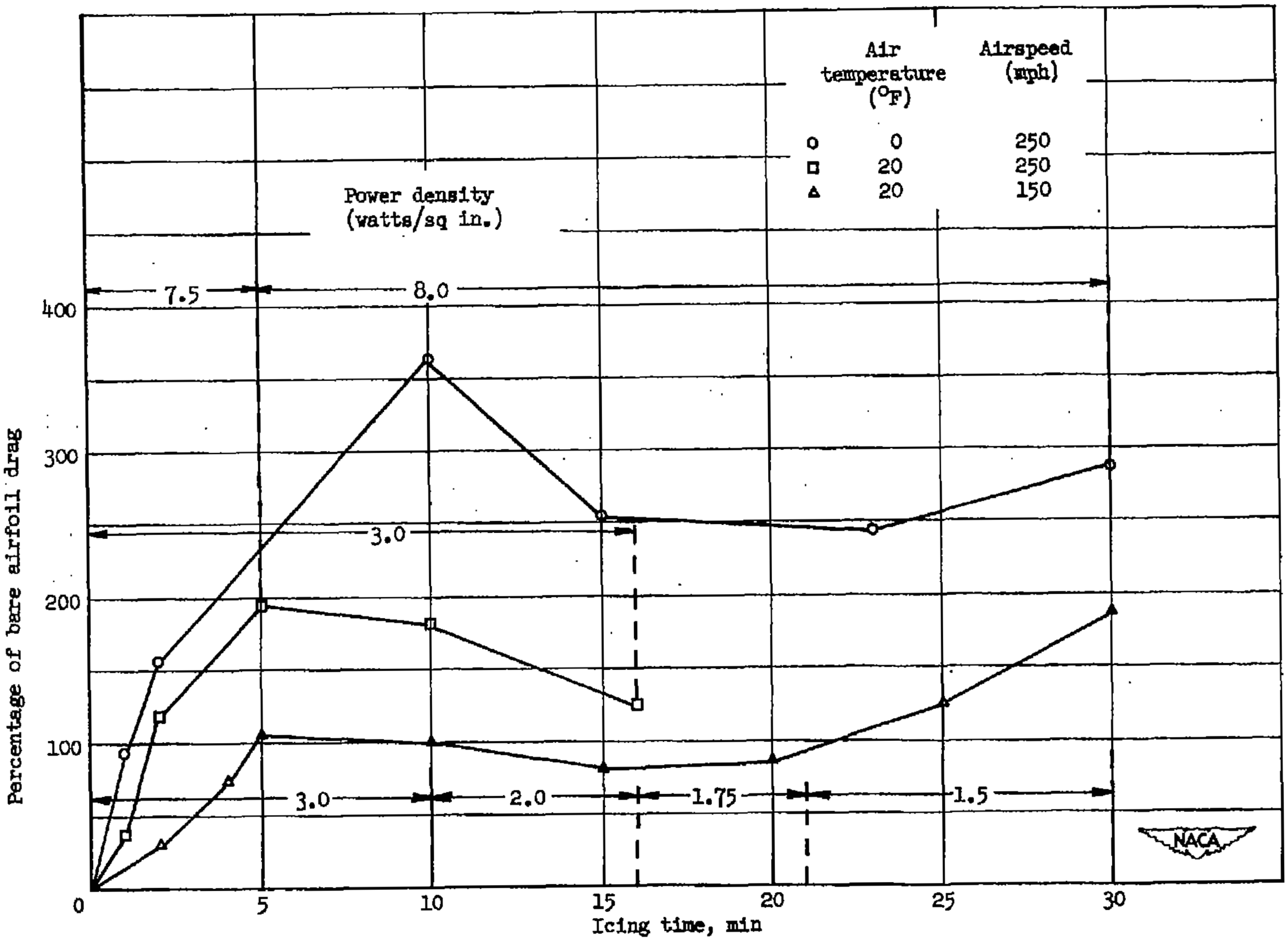


Figure 3. - Variation of drag with power density of leading-edge heater without operation of pneumatic system during icing. Angle of attack, 0°.

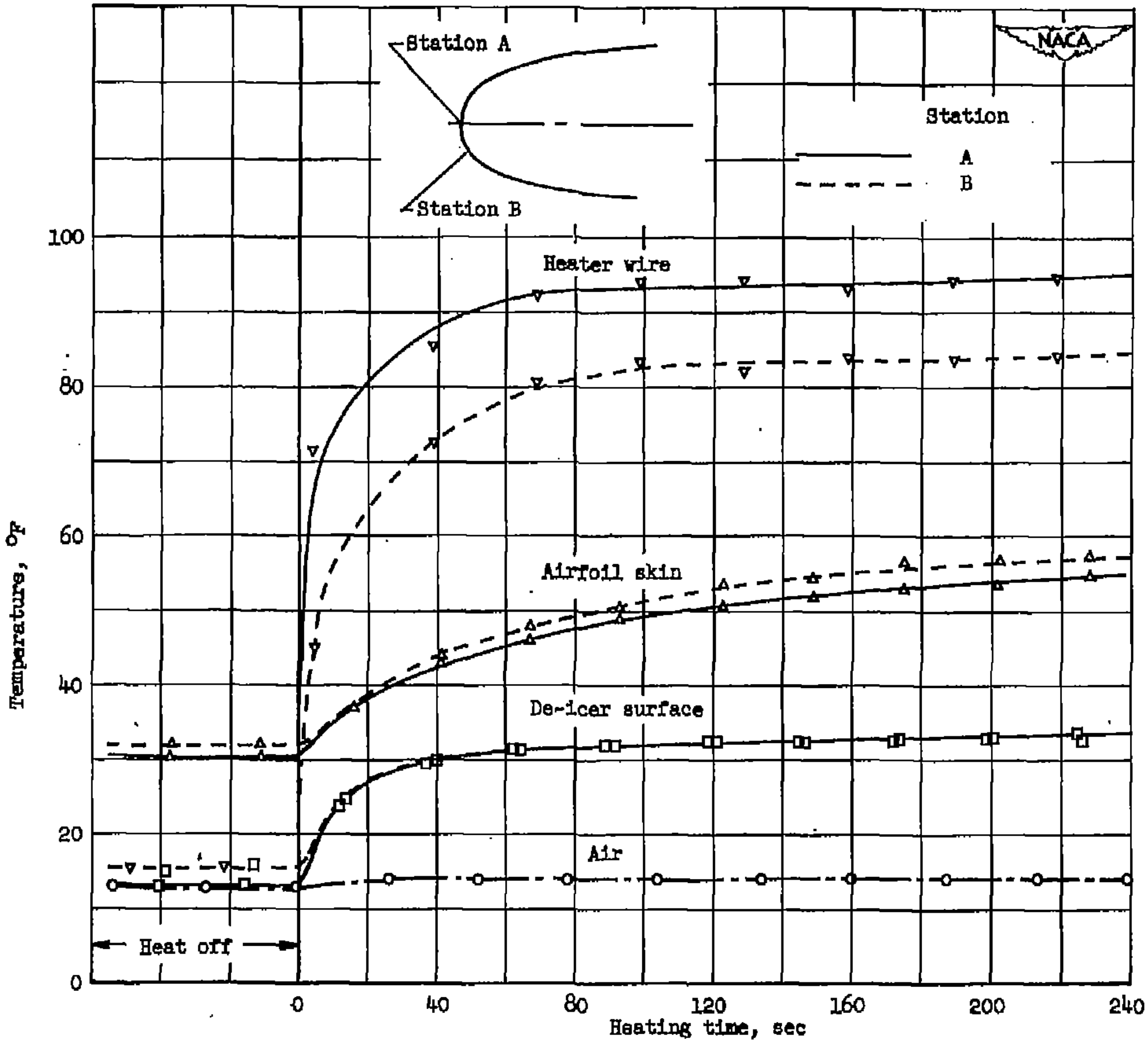


Figure 4. - Time history of heater temperatures during application of power. Airspeed, 250 miles per hour; air temperature, 14° F; angle of attack, 0°; power density, 5.2 watts per square inch.

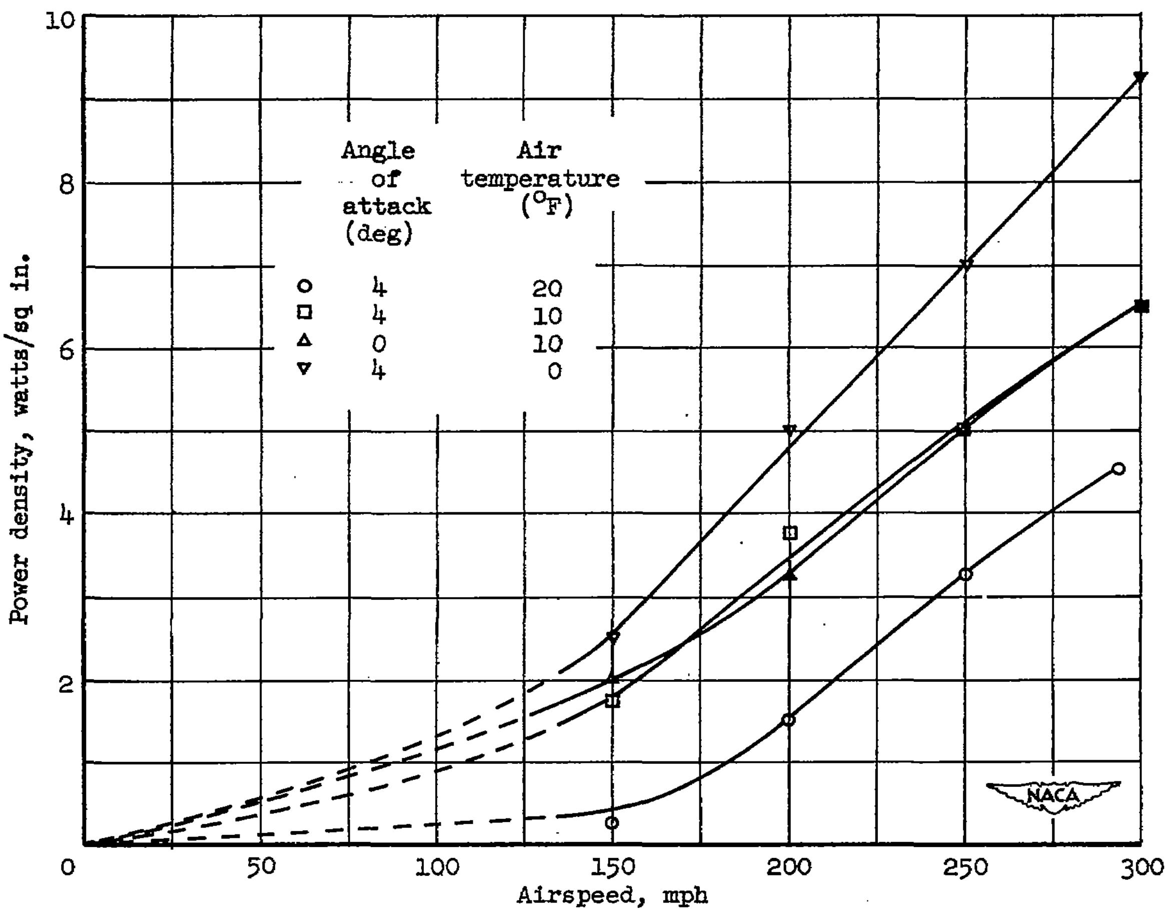
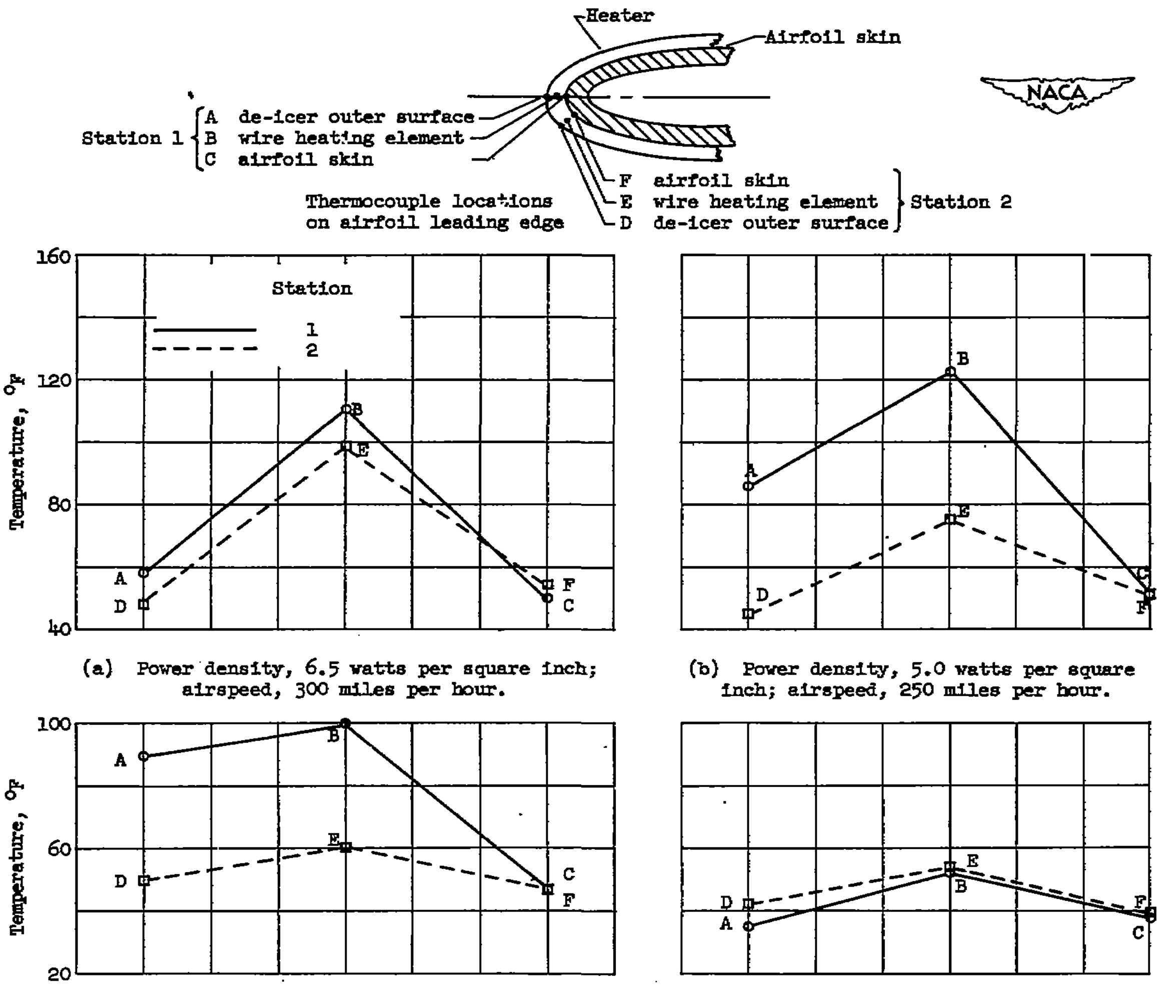


Figure 5. - Marginal power requirements for icing protection on leading edge of NACA 0018 airfoil section equipped with thermal-pneumatic de-icer.



(a) Power density, 6.5 watts per square inch; airspeed, 300 miles per hour.

(b) Power density, 5.0 watts per square inch; airspeed, 250 miles per hour.

(c) Power density, 3.25 watts per square inch; airspeed, 200 miles per hour.

(d) Power density, 2 watts per square inch; airspeed, 150 miles per hour.

Figure 6. - Temperature pattern for thermal area of thermal-pneumatic de-icer at marginal power densities during icing. Air temperature, 10° F; angle of attack, 0°; liquid-water content, 2 grams per cubic meter; mean effective droplet size, 35 microns.

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